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# $n$ -Channel Symmetric Motion-Compensated Multiple Description Coding for Video Communications over OFDM Networks<sup>†</sup>

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**Abstract**—We propose an  $n$ -channel symmetric motion-compensated multiple description (MD) coding and transmission scheme for the delivery of fine granular scalable (FGS) video over multicarrier orthogonal frequency division multiplexing (OFDM) systems, utilizing the concepts of partial and leaky predictions. We investigate the proposed MD coding and transmission scheme using a cross-layer design perspective. In particular, we construct the symmetric motion compensated MD codes based on the diversity order of the channel, defined as the ratio of the overall bandwidth of the system to the coherence bandwidth of the channel. We show that knowing the diversity order of a physical channel can assist an FGS video coder in selecting the motion compensation prediction point, as well as on the use of leaky prediction. More importantly, we illustrate how the side information can reduce the drift management problem associated with the construction of symmetric motion-compensated MD codes.

## I. INTRODUCTION

Multiple description (MD) source coding has recently emerged as an attractive framework for robust transmission over wired and/or wireless networks [1]. An MD source coder generates MDs such that each description individually describes the source with a certain level of fidelity. The multiple bitstreams are transmitted over the network, and the correctly received descriptions are then individually decoded and synergistically combined to enhance the end-user received quality. Due to the individually decodable nature of the MDs, the loss of some of the descriptions will not jeopardize the decoding of correctly received descriptions, while the fidelity of the received information improves as the number of received descriptions increases. In this paper, we propose an  $n$ -channel symmetric motion-compensated MD coding and delivery scheme for the transmission of fine granular scalable (FGS) video over multicarrier orthogonal frequency division multiplexing (OFDM) systems. To the best of our knowledge, the studies on motion-compensated MD source coding in the literature has been limited to  $n = 2$ . In this work, we focus on an arbitrary  $n$ .

Symmetric  $n$ -channel MD coding, characterized by  $(n+1)$ -tuples  $(R, D_1, D_2, \dots, D_n)$ , where  $D_i$  corresponds to the distortion for the reception of  $i$  descriptions, is a special case of the MD problem in which the distortion depends solely on the number of descriptions received. Fig. 1 illustrates a practical realization of symmetric  $n$ -channel MD (without motion compensation), by combining an embedded bitstream with unequal error protection (UEP) using maximum distance

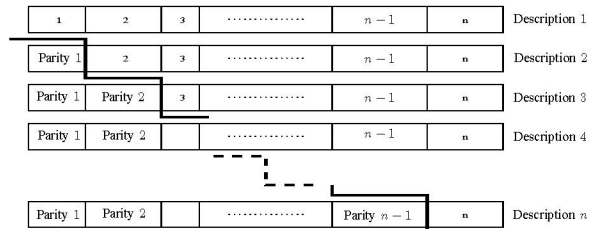


Fig. 1. FEC-MD:  $n$ -channel symmetric MD coding using maximum distance separable (MDS) erasure codes.

separable (MDS) erasure codes for the construction of multiple individually decodable descriptions. This is generally referred to as  $n$ -channel symmetric FEC-based multiple description coding (FEC-MD) [4], [5].

Most of the current state-of-the-art video codecs incorporate motion-compensated prediction (MCP). A high compression efficiency can hence be achieved through exploiting the temporal redundancy. However, the use of MCP also renders the compressed video extremely sensitive to channel impairments. Sometimes a single bit error or erasure can cause precipitous degradation due to error propagation as a result of predictor-mismatch between the encoder and decoder. This is the so-called “drift” problem. Hence, motion compensated MD video coding faces the unique challenge of mismatch control, as a result of the variety of different predictions that may be used at the decoder [2].

The FGS video coding was proposed by the MPEG-4 committee to code for dynamic channel conditions and increasing heterogeneous network environments [3]. It partitions the compressed bitstream into a base layer (BL) and a progressively encoded enhancement layer (EL) such that the EL can be truncated at any arbitrary location. This specific property provides a reconstructed video quality that increases with the number of bits decoded. However, in the FGS MPEG-4 coder, while the BL is generated by MCP, there is no MCP for the FGS EL. This prediction structure provides an inherent robustness against channel impairments and completely avoids error propagation (drifting effects) due to corruption of the EL. The embedded structure also facilitates the development of prioritized transport protocols and rate control algorithms. For example, one can combine the FGS bitstream with UEP using MDS for construction of FEC-based MD and achieve a much more robust delivery system [4], [5].

However, due to the lack of MCP, conventional FGS coding suffers from reduced compression efficiency. To fix this, several algorithms have been proposed in the literature [6],

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[7]. The MC-FGS coding proposed in [6] introduces an MCP loop in the EL (FGS layer) by using the motion vectors (MVs) and prediction modes from the BL. The tradeoff in coding efficiency and error resilience is achieved by controlling the amount of the EL (the number of bitplanes) used for the prediction. However, MC-FGS still suffers from error propagation when the portion of the EL (lower bitplanes) used for prediction is lost. A robust FGS (RFGS) was proposed in [7], and combines the 2-loop prediction with drift attenuation using leaky prediction techniques [8]. By scaling down the reference frame by a leak factor  $\alpha \in [0, 1]$ , error propagation will decay faster in the temporal direction. The basic idea of these schemes is to partially include MCP in the FGS EL in a well-controlled manner so as to achieve a balance between coding efficiency and error resilience.

In this paper, we illustrate how the above basic ideas can be extended to the construction of  $n$ -channel symmetric motion-compensated MD coding. As shown in [9] and [10], to achieve the best performance, MD coding generally requires the existence of *multiple independent* channels, or equivalently, MD coding and delivery schemes generally require the simultaneous consideration of the diversity order of a communication system. For example, in [9], multiple independent paths are *explicitly* created at the network layer through routing for the transmission of individually decodable descriptions. In [10], the authors explicitly consider the number of independent components, or, equivalently, the diversity order, existing at the physical layer in a mobile wireless OFDM system, and propose a cross-layer diversity technique which seamlessly combines the concept of channel coding across multiple independent components and FEC-based MD coding so as to achieve a better system performance. Hence, in this work, we investigate the proposed MD coding scheme using a cross-layer design perspective by taking into consideration the diversity order when constructing the MDs.

The rest of the paper is organized as follows. In Section II, we describe some technical preliminaries, including basics of the channel model used. In Section III, we provide a framework for the construction of  $n$ -channel symmetric motion-compensated MD coding. In Section IV, we provide simulation results and discussion. Finally, Section V gives a summary and conclusions.

## II. PRELIMINARIES

### A. System Description and Channel Model

In this work, we consider a frequency-selective environment and use a block fading channel model to simulate the frequency selectivity. The model has been shown to provide a good approximation to the physical channel, while simultaneously maintaining its analytic tractability [11]. In this model, the spectrum is divided into blocks whose size equals the channel coherence bandwidth ( $\Delta f_c$ ). Subcarriers in different blocks are considered to fade independently; subcarriers in the same block experience identical fades. We assume an OFDM system with an overall system bandwidth  $W_T$ , such that we can define  $N$  independent subbands. Each of the  $N$  independent subbands consists of  $M$  correlated subcarriers

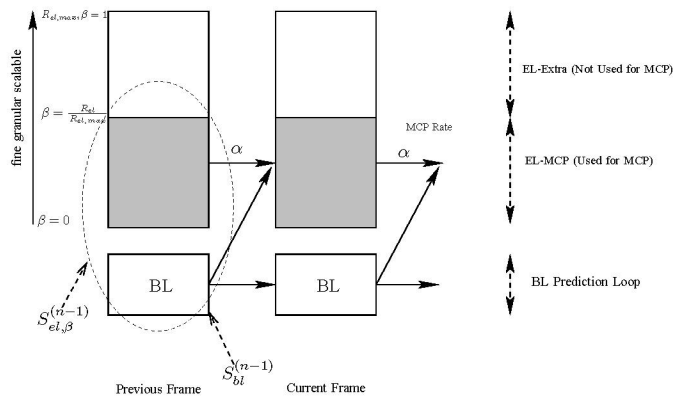


Fig. 2. A motion compensated FGS hybrid coder with leaky prediction.

spanning a total bandwidth of  $\Delta f_c$ . The total number of subcarriers in the OFDM system is equal to  $N \times M$ .

In general, the maximum achievable diversity gain is the order of diversity,  $N$ . Note that  $N = 1$  corresponds to a flat-fading environment, while  $N > 1$  corresponds to a frequency-selective environment. In the time domain, we assume the channel experiences slow Rayleigh fading. We do not consider channel coding plus interleaving in the time domain. Generally, due to the bursty nature of the errors associated with a slow-fading environment (as considered in this paper), channel coding plus intra-packet interleaving in the time domain become less effective [12].

### B. Motion-Compensated FGS with Leaky Prediction

Fig. 2 illustrates the general framework for an MC-FGS coder with leaky prediction [7], [13] which introduces an attenuated MCP into the single FGS EL. In this work, for simplicity, we assume reliable delivery of the BL, including coding modes and MVs [7], [13].

Since the EL is encoded in an embedded manner, all or part of the EL can be used for prediction for the next EL. The EL MCP loop uses an improved reference frame that combines the BL and the partial EL. As shown in the figure, we denote the partial EL used for MCP as EL-MCP, and the other part, used for enhancement only, is denoted EL-Extra. The quality of the reference frame depends on the amount of the EL being included in the EL prediction loop, as well as the attenuation factor (leak factor). As the amount of the EL used for the prediction of the next frame increases, a higher coding efficiency can be achieved. On the other hand, reconstruction errors will accumulate if the portion of the EL used for MCP is not available at the decoder. If we assume  $R$  to be the bitrate for EL-MCP, and  $R_{el, max}$  to be the maximum bitrate for the FGS EL, we can define a parameter  $\beta = R/R_{el, max}$  such that  $\beta$  represents the portion of the EL to be included in the MCP in the EL. Hence,  $\beta$  can be used as an adaptive parameter for trading off coding efficiency and error resilience. Note that  $\beta = 0.0$  corresponds to the conventional FGS scheme in which the EL is completely excluded from the MCP. As stated previously, FGS can be achieved by employing different coding methods for the residues. Depending on the coding method,  $\beta$  can be defined in different ways. For example,

both [13] and [7] considered using the number of bitplanes to trade off the compression efficiency and the error resilience. To be independent of the specific encoder implementation, we use the theoretical framework developed by Girod for the study of MCP hybrid coders [14] and allow  $\beta$  to vary continuously.

The leak factor  $\alpha \in [0, 1]$  downscales the portion of the FGS EL-MCP before it is incorporated into the MCP loop [7]. It is targeted to ameliorate the effects of error propagation caused by the loss of the EL. As a result, the reference  $\hat{S}_{el,\beta}^{(n-1)}$  for the prediction of the current EL is a weighted sum of the BL  $S_{bl}^{(n-1)}$  and the partial EL  $S_{el,\beta}^{(n-1)}$ , i.e.,

$$\hat{S}_{el,\beta}^{(n-1)} = (1 - \alpha)S_{bl}^{(n-1)} + \alpha S_{el,\beta}^{(n-1)} \quad (1)$$

When the leak factor  $\alpha$  is set to zero, the EL is also completely excluded from MCP, resulting in the conventional FGS codec, while  $\alpha = 1.0$  corresponds to the MC-FGS [13] without leaky prediction, which has the best coding efficiency and the least error resilience. Hence, by choosing  $\alpha$  between 0 and 1, one trades off compression efficiency and error resilience. There are thus two separate parameters which we can adjust to trade off between error resilience and compression performance:  $\beta$ , which controls how much of the EL will be used for prediction; and  $\alpha$ , which controls how much weight will be given to that EL portion.

### III. $n$ -CHANNEL SYMMETRIC MOTION-COMPENSATED MD CODING

#### A. Key Challenges

As stated previously, motion compensated MD video coders face the unique challenge of mismatch control, as a result of the variety of different predictions that may be used at the decoder [2]. Consider a generic 2-channel non-symmetric MD system which can be characterized by the quintuple  $(R_1, R_2, D_1^{(1)}, D_1^{(2)}, D_2)$ , where  $R_1$  and  $R_2$  are the bitrates of the two individual descriptions, 1 and 2, respectively.  $D_1^{(1)}$  is the distortion when description 1 is received,  $D_1^{(2)}$  is the distortion when description 2 is received and  $D_2$  is the distortion when both descriptions are received. As a result, there are three possible prediction states at the decoder, corresponding to the successful reception of description 1, description 2, or both descriptions. Each of the 3 states can form its own prediction loop. Whenever the encoder uses a predictor that depends on a state not available at the decoder, there will be a mismatch between the prediction loops at the encoder and decoder. Similar to single description (SD) MCP coding, this mismatch between encoder and decoder will trigger error propagation or drift.

To avoid such mismatch, one can, for example, construct two independent prediction loops, each based on a single-channel reconstruction. At the expense of decreased compression efficiency, this can completely avoid the mismatches for the side decoders, even when one of the two descriptions is lost [15], [16]. Hence, as opposed to the traditional predictive coding paradigm that systems should not be designed to allow drift/mismatch, there is a growing interest in predictive coding schemes (both SD and MD) that allow some drift/mismatch

so as to improve the overall compression efficiency. This is called the drift-managed approach [16].

A drift-managed approach does not preclude drift in the prediction strategy. Instead, it allows drift/mismatch to be introduced incrementally, and encompasses drift-free as a special case. In other words, a drift-managed approach optimizes the system performance by trading off the compression efficiency and the amount of mismatch, allowing the drift-free solution to emerge when it is optimal. The design paradigm can be applied to the construction of  $n$ -channel symmetric motion-compensated MD codes. One can, for example, assign  $m \in [0, n]$  descriptions as a reference for the temporal prediction, where  $m = 0$  corresponds to the drift-free case. Note that if the number of received descriptions  $m' < m$ , there will be a mismatch. Generally, a higher prediction efficiency can be achieved by using a larger  $m$ . However, this comes at a price of greater probability of mismatch.

More importantly, although the number of descriptions to be included for the MCP has often been thought of as a “fine-tuning” method for trading off compression and error resilience, and allowing drift to be introduced incrementally (see [2], Section III-G), the correlation among the subcarriers/channels may make this less effective. For instance, if  $M$  out of  $n$  descriptions are delivered through  $M$  highly correlated channels, these  $M$  descriptions are likely to be lost or received all together. The encoder should decide whether to include  $M$  more or  $M$  fewer descriptions in the MCP loop, instead of attempting to fine-tune by including 1 more or 1 fewer description in the loop, because the correlated nature of the subcarriers makes it unlikely that that number of descriptions would be received. The effect becomes more significant when  $M$  is large, or, equivalently, when the order of diversity is small. This erratic behavior due to the simultaneous loss of several descriptions transmitted through highly correlated channels may greatly affect the degree of encoder-decoder mismatch, and hence the effectiveness of drift control, which may subsequently result in severe unexpected error propagation.

#### B. Motion-Compensated FEC-MD Coding

In this section, we describe a coding scheme that converts a motion-compensated FGS (embedded) bitstream into  $n$ -channel symmetric MD using MDS erasure codes. In Fig. 3, we illustrate this construction. In particular, we extend the cross-layer diversity technique proposed in [10], in which multiple independent descriptions are constructed using an FEC-MD approach, explicitly considering the order of diversity available at the physical layer of a mobile wireless OFDM system. Fig. 3(a) shows a typical FGS EL, in which the bitstream is divided into EL-MCP and EL-Extra. Less important EL-Extra bits can be discarded as illustrated, based on available bandwidth and channel conditions.

As shown in Fig. 3(b), similar to the construction of  $n$ -channel symmetric MD without motion compensation, contiguous information symbols are spread across the MDs. The information symbols are protected against channel errors using systematic  $(n, k)$  MDS codes, with the level of protection depending on the relative importance of the information symbols.

The reception of at least any  $\phi_{th}$  descriptions out of a total of  $n$  descriptions allows us to start reconstructing the source. In the figure,  $M$  corresponds to the number of highly correlated subcarriers in a subband, and  $N$  corresponds to the number of independent subbands of the frequency spectrum. Generally, an  $(n, k)$  MDS erasure code can correct up to  $(n - k)$  erasures. In Fig. 3(b), the symbols above the boundary are information symbols, while those below are parity symbols. However, unlike the conventional FEC-MD approach, the information symbols here can be further classified into ones carrying MCP information (i.e., the EL-MCP), and ones carrying information for enhancing the video quality without being used for MCP (i.e., the EL-Extra). EL-MCP is  $\alpha$ -attenuated before it is incorporated into the EL MCP loop. Since the number of descriptions used for MCP is  $m$ , the reception of  $m' < m$  descriptions leads to encoder-decoder mismatch.

Mathematically, we formulate the optimization for the construction of  $n$ -channel symmetric motion compensated MDs as follows. Consider a system with  $N$  i.i.d. subbands, each with  $M$  subcarriers and the packet size of individual descriptions equal to  $L$  code symbols. Hence, there are  $N_t = N \times M$  subcarriers (descriptions). We assume that for codeword  $l$ ,  $c_l$  code symbols are assigned to information symbols. Hence, the reception of any  $m' > \phi_{th}$  descriptions leads to a reconstructed video quality  $D(R_{m'})$ , where  $R_{m'}$  is the information rate, given by symbols

$$R_{m'} = \sum_{\{l: c_l \leq m'\}} c_l. \quad (2)$$

Given the rate-distortion (RD) curve  $D(\bullet)$  and the packet loss probability mass function  $P_J(j)$ , where  $j = N_t - m'$  is the number of lost packets, which depends on, among other things, the diversity order  $N$  of a communication system as well as the channel conditions [10], we can then minimize the expected distortion

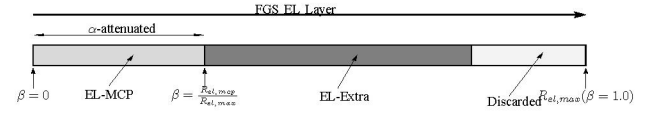
$$E^*[D] = \min_{\{c_l, \beta, \alpha\}} \left\{ \sum_{j=0}^{N_t - \phi_{th}} P_J(j) D(\beta, \alpha, R_{m'}) + \sum_{j=N_t - \phi_{th} + 1}^{N_t} P_J(j) D_B \right\}, \quad (3)$$

where  $D_B$  corresponds to the distortion when less than  $\phi_{th}$  descriptions are received and so the decoder must reconstruct the video source using the BL only. Note that  $R_{m'} < \beta R_{el, max}$  represents the situation of encoder-decoder predictor mismatches. In this paper, the RD curves  $D(\bullet)$  are obtained using the information-theoretic approach proposed for the study of an MCP hybrid coder [14], and was subsequently extended to scalable hybrid coders [17]–[19] because it predicted results that conformed to operational observations [17], [18].

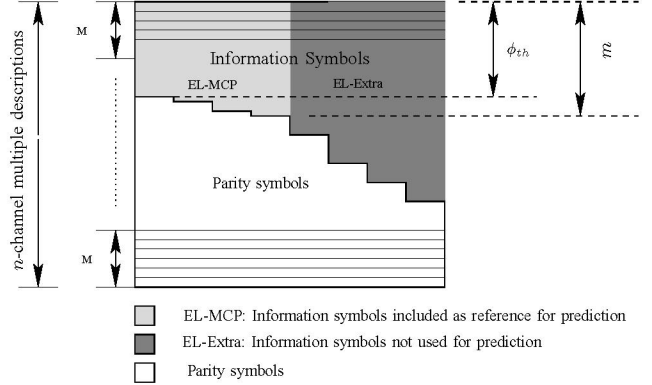
#### IV. RESULTS AND DISCUSSION

We assume the power spectral density of the input video signal  $\{s\}$  to be [14]

$$\Phi_{ss}(\Lambda) = \begin{cases} \frac{2\pi}{\omega_0^2} \left(1 + \frac{\omega_x^2 + \omega_y^2}{\omega_0^2}\right)^{-3/2} & \text{for } |\omega_x| \leq \pi f_{sx} \\ & \text{and } |\omega_y| \leq \pi f_{sy} \\ 0 & \text{otherwise,} \end{cases} \quad (4)$$



(a) An FGS (embedded) EL bitstream



(b) Motion Compensated FEC-MD coding

Fig. 3.  $n$ -channel symmetric motion-compensated multiple description coding using MDS erasure codes.

where  $f_{sx}$  and  $f_{sy}$  denote the sampling frequencies when  $\{s\}$  is spatially sampled at the Nyquist rate. As in [14], we choose  $\omega_0 = \frac{\pi f_{sx}}{42.19} = \frac{\pi f_{sy}}{46.15}$ , which corresponds to a horizontal and vertical correlation of 0.928 and 0.934, respectively. The parameters are chosen to match the model given by (4) with real video signals [14]<sup>1</sup>.

The probability density function of the estimated MV error is modeled as zero mean Gaussian with variance  $\sigma_{\Delta d}^2$ . Hence, we have the characteristic function given by [14]

$$P(\Lambda) = \exp \left[ -\frac{\sigma_{\Delta d}^2}{2} (\omega_x^2 + \omega_y^2) \right], \quad (5)$$

and we choose the spatial filter as  $F(\omega_x, \omega_y) = P^*(\omega_x, \omega_y)$  [14].

The embedded bitstream was converted to 128 parallel bitstreams using an  $n$ -channel symmetric motion-compensated FEC-MD encoder. The 128 descriptions were mapped to the OFDM system with 128 subcarriers. We used RS codes for error protection, and there were 8 bits per RS symbol. The packet size was set equal to 512 bits, corresponding to 64 RS symbols. Each packet corresponded to one description. We assumed slow Rayleigh fading with normalized Doppler spread  $f_{nd} = 10^{-3}$  in the time domain. We used coherent QPSK modulation and set channel SNR to 20.0 dB.

##### A. Partial Prediction: EL-MCP ( $\beta$ )

In Fig. 4, we show the rate-distortion functions of an MC-FGS hybrid coder for  $\sigma_{\Delta d}^2 = 0.04$  with various amounts

<sup>1</sup>In [14], the format of the input video signal is  $320 \times 288$  pixels. Here, to match with the system bandwidth, we consider a QCIF format with resolution  $170 \times 144$  pixels.

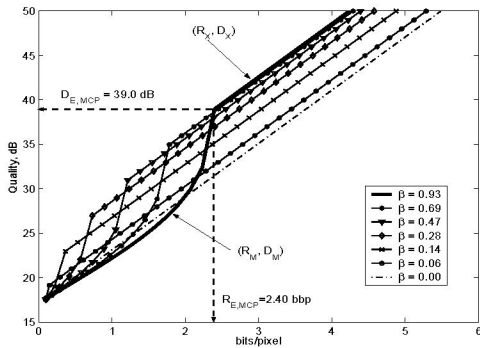


Fig. 4. Rate-distortion functions for the MC-FGS with various MCP rates ( $\beta$ ) without leaky prediction,  $\sigma_{\Delta d}^2 = 0.04$ .

of EL-MCP. We fixed the coding rate of the BL to be  $R_B = 0.1$  bits/pixel, and this rate produced a quality  $D_B \triangleq 10 \log_{10} \frac{1}{MSE^2} = 17.6$  dB. As can be seen from the figure, generally, a higher EL MCP rate gives a better overall compression performance if the video is decoded above the MCP rates, i.e., if there is no mismatch between the encoder and decoder predictors. The rate distortion performance for decoding above the MCP rate is indicated by  $(R_X, D_X)$ . However, if the decoding is below the MCP rate used for the prediction, there is a precipitous drop in performance. For example, in Fig. 4, the thick line indicates a choice of the MCP rate equal to 2.40 bpp, which produces a reference with  $D_{E,mcp} = 39.0$  dB. If the amount of information received at the decoder is less than the 2.40 bpp, there is a substantial decrease in final video quality, with performance illustrated by the rate distortion performance curve  $(R_M, D_M)$ . This is because, at the encoder, the information up to the MCP rate is used as the reference for the prediction of the next frame, while at the decoder, a lower fidelity reference frame (below the MCP rate) is used. This mismatch causes error propagation and loss of performance. The portion of the curves denoted by  $(R_X, D_X)$  corresponds to the extra information (EL-Extra), which is only used for enhancing the video quality, without being used for motion compensation.

Fig. 5 illustrates the construction of the MDs using the MD-FEC approach for an OFDM system with a diversity order  $N = 4$ , which corresponds to a system in which the ratio of the overall bandwidth to the coherence bandwidth is 4 : 1. In particular, we show the optimal parity protection levels for both the EL-MCP and the EL-Extra for various  $\beta$ . We define  $R_{el,max} = 128$  descriptions  $\times$  64 RS symbols/description  $\times$  8 bits/RS symbols. In general, since the relative importance of an embedded bitstream is strictly decreasing, this results in tilted boundaries across the subcarriers, as shown in the figure, which corresponds to decreasing levels of parity protection for the codewords on the right. The vertical lines extending downward from the top show the boundaries between the EL-MCP information symbols and EL-Extra information symbols, for three values of  $\beta$ . By comparing the boundaries for various  $\beta$ , one can notice the effects of the inclusion of a partial MCP loop in the EL. In particular, the boundaries show that EL-MCP is more strongly protected than EL-Extra, due to the

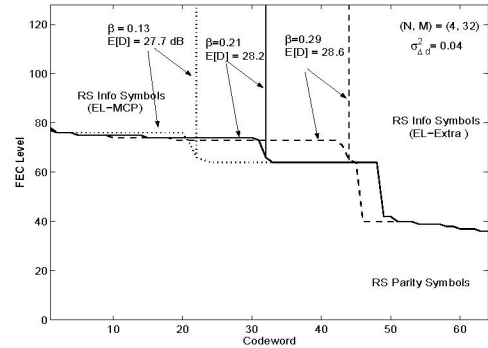


Fig. 5. The RS symbol boundaries for the  $n$ -channel symmetric motion-compensated MD codes for  $(N, M) = (4, 32)$  for  $\sigma_{\Delta d}^2 = 0.04$ .

drift problem associated with the loss of this information.

The boundaries separating the information symbols and parity symbols exhibit a stepwise behavior. This is mainly due to the highly correlated fading nature of the subcarriers within a subband, which results in the simultaneous loss of several MDs when the correlated subcarriers are under a deep fade. We refer interested readers to [10] for more detailed discussions.

In Fig. 6, we show the boundaries for the construction of  $n$ -channel symmetric motion-compensated MD coding for various orders of diversity, or, equivalently, different numbers of independent subbands,  $N$ . In particular, we show the optimal allocation of the parity symbols and the EL information symbols for a fixed compression scheme with  $\beta = 0.17$  for systems with diversity orders  $N = 2, 16, 32$  and 128. As can be observed, the boundaries show some similar features to those from conventional  $n$ -channel symmetric MDs without motion compensation [10]. For instance, as the order of diversity increases, the tilting of boundaries separating the parity symbols and information symbols decreases, signifying decreasing reliance on UEP. The decrease in  $N$  also leads to increasing staircase behavior at the boundaries due to the increase in the correlation among the subcarriers. Notice that the boundaries show similar patterns as in Fig. 5. In particular, most of the EL-MCP is strongly protected against channel errors, while the last portion the EL-MCP is relatively less strongly protected, thus allowing occasional minor mismatch of the encoder and decoder predictors. However, Fig. 6 also illustrates the impact of the order of diversity on the construction of the multiple individual descriptions. Specifically, as  $N$  increases, the EL-MCP symbols are spread across a larger number of descriptions/subcarriers. This may be considered undesirable from a pure source coding point of view, as more descriptions have to be received to avoid encoder-decoder mismatch. However, with a higher diversity order, the confidence interval for the number of descriptions to be correctly received decreases, meaning that the variance in the number of correctly received description decreases. As a result, the EL-MCP can be carried by a larger number of subcarriers/descriptions.

As stated previously, a larger MCP rate leads to higher coding efficiency at the expense of poorer error resilience.

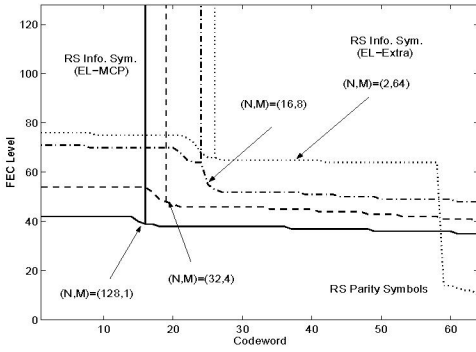


Fig. 6. The RS symbol boundaries for the  $n$ -channel symmetric motion-compensated MD codes for different numbers of independent channels  $N$ .

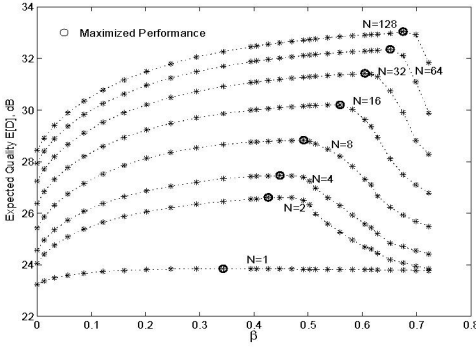


Fig. 7. The distortion performance against different  $\beta$  (EL-MCP) for OFDM systems with different orders of diversity  $N$ .

Hence, the major issue is how much information should be included for MCP so as to achieve a balanced tradeoff between the compression efficiency and error resilience. In Fig. 7, we demonstrate that knowing the diversity order can help to define the amount of EL-MCP, in terms of  $\beta$ , and hence, the construction of the motion compensated MDs. We plot the distortion performance against  $\beta$  for systems with different diversity orders. In the plots, we also mark with a circle ( $\circ$ ) the optimal selections of EL-MCP ( $\beta_{opt}$ ). As can be observed, generally a better performance can be achieved with a higher diversity order.

### B. Leaky Prediction ( $\alpha$ EL-MCP)

In this section, we study leaky prediction for controlling drift. Leaky prediction scales down the information used as the reference for MCP by a leak factor  $\alpha \in [0, 1]$  so as to speed the decay of error propagation temporally. In Fig. 8, we show the performance for a system with  $R_{E,MCP} = 1.2$  bpp, corresponding to  $\beta = 0.46$ , for  $\alpha = 0.72$  and  $1.00$ . As can be seen, as  $\alpha$  increases, the quality of the reconstructed video improves if the video is decoded above the MCP rate. However, if the decoding rate is below the MCP rate, the use of a larger leak factor  $\alpha$  also leads to a more severe drop in the final video quality, indicating poorer error resilience of the compressed video.

In Fig. 9, we show the optimal boundaries for the construction of motion compensated symmetric MDs for an OFDM system with diversity order  $N = 8$ . We fixed the MCP

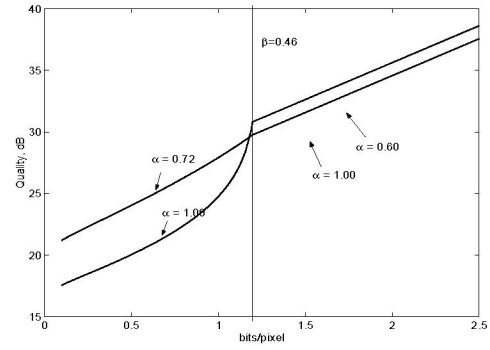


Fig. 8. Rate distortion functions of MC-FGS with leaky prediction,  $\sigma_{\Delta d}^2 = 0.04$ .

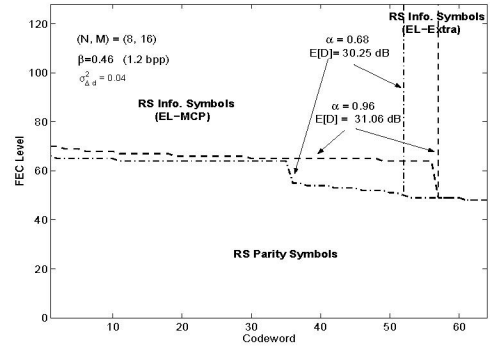


Fig. 9. The RS symbol boundaries for the  $n$ -channel symmetric motion-compensated MD codes for an  $(N, M) = (8, 16)$  OFDM system with EL-MCP fixed at  $\beta = 0.46$  (1.2 bpp) for different  $\alpha$ 's.

rate  $R_{E,MCP} = 1.2$  bpp, or, equivalently  $\beta = 0.46$ . The leak factors for the MDs are  $\alpha = 0.68$  and  $\alpha = 0.96$ . By comparing the two boundaries, one can notice the overall lower protection level of the RS parity symbols for  $\alpha = 0.68$ , indicating increasing error resilience of the  $\alpha$ -attenuated motion-compensated MDs to predictor mismatch.

Fig. 10 shows the distortion performances versus  $\alpha$  for OFDM systems with different  $N$  with the MCP rate fixed at  $R_{E,MCP} = 1.2$  bpp. Each line represents distortion performance of an OFDM system with the same order of diversity with different  $\alpha$ . In the plots, we mark with the symbol ( $\circ$ ) the optimal leak factors  $\alpha_{opt}$  for each curve. As can be observed, when the diversity order  $N$  decreases, ( $\alpha_{opt}$ ) moves to the left, corresponding to putting less weight on the EL-MCP. This is because the highly correlated nature of the subcarriers within a subband can lead to simultaneous loss of multiple MDs, creating severe predictor mismatch. The drift due to the simultaneous loss of multiple MDs as a result of the erratic behavior of the channel becomes more severe when the order of diversity is small. Therefore, a smaller leak factor is preferred so as to reduce the weight of the EL-MCP.

### C. Optimized Performance by jointly optimizing $\alpha$ and $\beta$

In Fig. 11, we illustrate that the performance of the  $n$ -channel symmetric motion compensated MDs can be optimized by jointly choosing the EL-MCP, in terms of  $\beta$ , and the weight of the EL-MCP, in terms of  $\alpha$ , based on the order

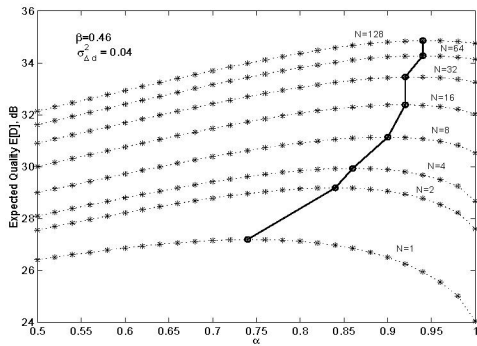


Fig. 10. The distortion performance vs.  $\alpha$  for OFDM systems with different orders of diversity  $N$  with  $\beta$  fixed at 0.46 corresponding to 1.2 bpp.

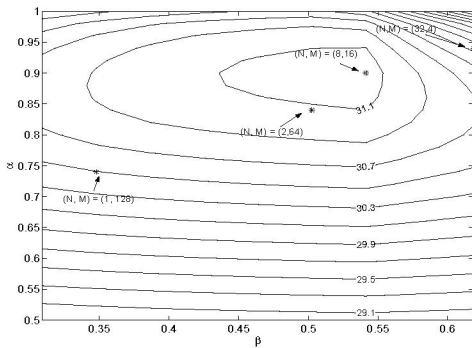


Fig. 11. The contour plot of the quality performance for different  $(\beta, \alpha)$  using the  $n$ -symmetric motion compensated MD codes for a system with diversity order  $N = 8$  and the optimal selection of  $(\alpha, \beta)$  for systems of different diversity orders  $N$  marked by (\*).

of diversity. In particular, we show contour plots of constant distortion for a system with diversity order  $N = 8$ . That is, each contour corresponds to a constant distortion achieved by different combinations of  $\alpha$  and  $\beta$ . In the figure, we indicate the optimal selection of  $(\alpha, \beta)_{opt}$  with the symbol (\*). In Fig. 11, we include the  $(\alpha, \beta)_{opt}$  point for systems with different diversity orders  $N = 2, 8, 16$  and  $32$ . As can be observed, as the diversity order  $N$  increases, the optimal operating point,  $(\alpha, \beta)_{opt}$ , moves to the upper right hand part of the figure, indicating a larger  $\alpha$  and  $\beta$  can be selected due to the increasing reliability and less erratic behavior of the system.

## V. CONCLUSION

In this paper, we studied the delivery of MC-FGS video employing an OFDM signal format at the physical layer for transmission over a frequency-selective, slow Rayleigh fading channel. We proposed an  $n$ -channel symmetric motion-compensated multiple description coding and transmission scheme, incorporating the concepts of partial and leaky predictions for mismatch control. We constructed the symmetric MDs employing a cross-layer diversity paradigm, in which we explicitly considered the diversity order of the OFDM system. We investigated the use of partial prediction, in terms of  $\beta$ , together with unequal error protection, to reduce the mismatch problem associated with the construction of motion-compensated MDs. We showed that knowing the diversity

order can assist an MC-FGS video coder in choosing the motion-compensation prediction rate. We also investigated the use of leaky prediction, in terms of  $\alpha$ , to achieve a tradeoff of compression efficiency and error resilience for motion-compensated MD codes. We studied two scenarios: constant-bitrate, in which the bitrate of the EL MCP is kept constant; and constant-distortion, in which the distortion of the EL MCP reference is kept constant. Finally, we showed that the problem of drift management can be reduced, and a better system performance can be achieved, by jointly optimizing  $\beta$ ,  $\alpha$  and the FEC protection level, and by incorporating the information on diversity order into the coding and delivery scheme using motion-compensated MD codes.

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